

## VU Research Portal

### Reconstruction of the eruptive activity on the NE sector of Stromboli volcano: timing of flank eruptions since 15 ka

Calvari, S.; Branca, S.; Corsaro, R.A.; De Beni, E.; Miraglia, L.; Norini, G.; Wijbrans, J.R.; Boschi, E.

***published in***

Bulletin of Volcanology  
2011

***DOI (link to publisher)***

[10.1007/s00445-010-0412-5](https://doi.org/10.1007/s00445-010-0412-5)

***document version***

Publisher's PDF, also known as Version of record

[Link to publication in VU Research Portal](#)

***citation for published version (APA)***

Calvari, S., Branca, S., Corsaro, R. A., De Beni, E., Miraglia, L., Norini, G., Wijbrans, J. R., & Boschi, E. (2011). Reconstruction of the eruptive activity on the NE sector of Stromboli volcano: timing of flank eruptions since 15 ka. *Bulletin of Volcanology*, 73(1), 101-112. [108]. <https://doi.org/10.1007/s00445-010-0412-5>

**General rights**

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal ?

**Take down policy**

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

**E-mail address:**

[vuresearchportal.ub@vu.nl](mailto:vuresearchportal.ub@vu.nl)

# Reconstruction of the eruptive activity on the NE sector of Stromboli volcano: timing of flank eruptions since 15 ka

Sonia Calvari · Stefano Branca · Rosa Anna Corsaro ·  
Emanuela De Beni · Lucia Miraglia · Gianluca Norini ·  
Jan Wijbrans · Enzo Boschi

Received: 27 July 2009 / Accepted: 12 September 2010 / Published online: 21 September 2010  
© Springer-Verlag 2010

**Abstract** A multidisciplinary geological and compositional investigation allowed us to reconstruct the occurrence of flank eruptions on the lower NE flank of Stromboli volcano since 15 ka. The oldest flank eruption recognised is Roisa, which occurred at ~15 ka during the Vancori period, and has transitional compositional characteristics between the Vancori and Neostromboli phases. Roisa was followed by the San Vincenzo eruption that took place at ~12 ka during the early stage of Neostromboli period. The eruptive fissure of San Vincenzo gave rise to a large scoria cone located

below the village of Stromboli, and generated a lava flow, most of which lies below sea level. Most of the flank eruptions outside the barren Sciara del Fuoco occurred in a short time, between ~9 and 7 ka during the Neostromboli period, when six eruptive events produced scoria cones, spatter ramparts and lava flows. The Neostromboli products belong to a potassic series (KS), and cluster in two differently evolved groups. After an eruptive pause of ~5,000 years, the most recent flank eruption involving the NE sector of the island occurred during the Recent Stromboli period with the formation of the large, highly K calc-alkaline lava flow field, named San Bartolo. The trend of eruptive fissures since 15 ka ranges from N30°E to N55° E, and corresponds to the magma intrusions radiating from the main feeding system of the volcano.

Editorial responsibility: B. van Wyk de Vries

**Electronic supplementary material** The online version of this article (doi:10.1007/s00445-010-0412-5) contains supplementary material, which is available to authorized users.

S. Calvari (✉) · S. Branca · R. A. Corsaro · E. De Beni ·  
L. Miraglia · E. Boschi  
Istituto Nazionale di Geofisica e Vulcanologia,  
Sezione di Catania,  
Piazza Roma 2,  
95123 Catania, Italy  
e-mail: sonia.calvari@ct.ingv.it

G. Norini  
Dipartimento di Scienze Geologiche e Geotecnologiche,  
Università degli Studi di Milano-Bicocca,  
Piazza della Scienza 4,  
20126 Milan, Italy

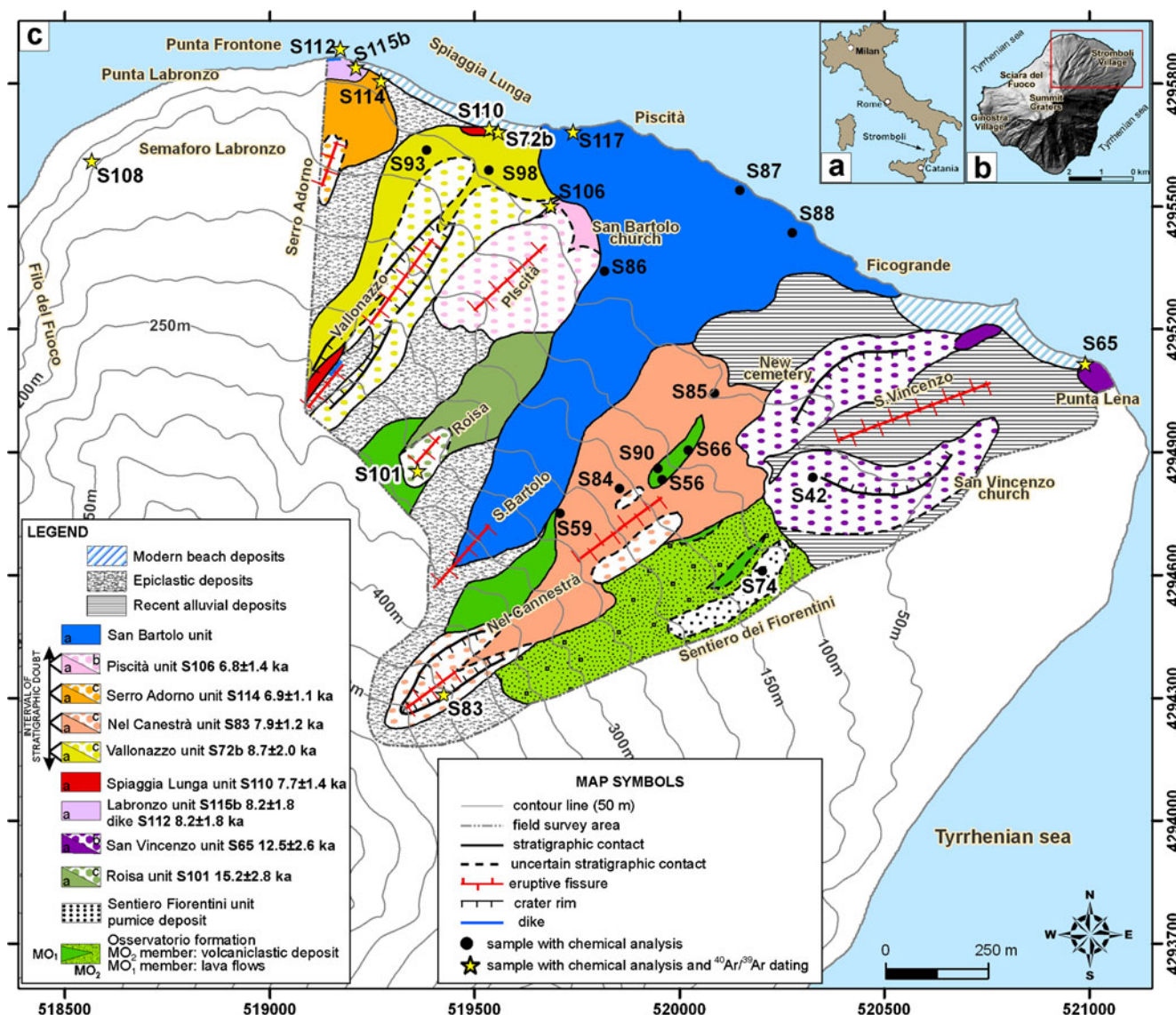
G. Norini  
Computational Geodynamics Laboratory, Centro de Geociencias,  
Universidad Nacional Autonoma de Mexico,  
Campus Juriquilla-UNAM, Blvd Juriquilla 3001,  
76230 Querétaro, Mexico

J. Wijbrans  
Faculteit der Aardwetenschappen, Vrije Universiteit,  
Amsterdam, The Netherlands

**Keywords** Stromboli volcano · Stratigraphy ·  
Neostromboli · Bulk rock composition · Flank eruptions ·  
Eruptive fissures

## Introduction

Stromboli volcano (Fig. 1a) is renowned worldwide for its continuous and mild explosive activity that has remained almost constant over the last 2,000 years (Rosi et al. 2000). Every few years very violent explosions occur, here called paroxysms (Barberi et al. 1993; Bertagnini et al. 1999; Calvari et al. 2006), producing ejecta that can reach the inhabited areas lying less than 2 km from the summit craters. Effusive activity is rare when compared to Etna (Branca and Del Carlo 2005), which has a frequency of one effusive eruption every 10 years (Barberi et al. 1993). At Stromboli, effusion of lava in historic times apparently exclusively involved the barren Sciara del Fuoco depres-



**Fig. 1** **a** Geographic location of Stromboli Island. **b** DEM of Stromboli island, with the red square indicating the study area represented in **c**. **c** geological map of the study area and location of the samples. In the legend of the geological map: a=lava flow, b=scoria cone and c=spatter ramparts

sion (Fig. 1b), with virtually no danger to the population apart from tsunami waves triggered by hot avalanches or landslides entering the sea (e.g. Rittmann 1931; Bonaccorso et al. 2003).

The most recent geological map of the island and radiometric K/Ar dating (Keller et al. 1993; Hornig-Kjarsgaard et al. 1993; Gillot and Keller 1993) distinguish four major periods of activity and suites of lava compositions. Paleostromboli (PST) spans from 110 to  $35.0 \pm 6.0$  ka, and comprises high-K calc-alkaline (PST I), calc-alkaline (PST II), and high-K calc-alkaline to shoshonitic compositions (PST III). The Scari complex, located on the ENE flank of the island, is intermediate between Paleostromboli and Vancori, has transitional to shoshonitic compositions,

and an age of  $\sim 35$  ka. Vancori (35 to 13 ka) shows shoshonitic compositions and is divided into lower ( $26.2 \pm 3.2$  ka), middle ( $21.0 \pm 6.6$  ka and  $22.0 \pm 2.80$  ka) and upper ( $13.0 \pm 1.9$  ka) groups, with the last partially overlapping, in terms of major element compositions, with the base of Neostromboli ( $13.8 \pm 1.5$  to  $5.6 \pm 3.3$  ka) having leucite-bearing (potassic) shoshonitic products (Francalanci et al. 1989). Recent Stromboli is considered younger than 5.0 ka, shows shoshonitic and high-K calc-alkaline rocks essentially emplaced within the Sciara del Fuoco, but also comprises the San Bartolo lava field that covers the NE flank of the island (Fig. 1).

The previous geological survey (Keller et al. 1993) pointed out that effusive flank activity outside the Sciara

del Fuoco was rare and old, being mainly of Neostromboli age, such as the shoshonitic Nel Cannestrà lava flow (Gillot and Keller 1993; Hornig-Kjarsgaard et al. 1993). There are, however, no isotopic ages for the Nel Cannestrà lava flow at present, and the Neostromboli age was inferred only on the basis of compositional affinity (Hornig-Kjarsgaard et al. 1993). Above the mostly undifferentiated products of the Neostromboli activity, only the San Bartolo fissure and its lava flow field have been mapped on the NE flank of the volcano (Keller et al. 1993). Archeomagnetic datings based on paleo-intensity measurements of the Earth's magnetic field (Arrighi et al. 2004) have suggested a Roman age,  $100 \pm 100$  AD, for the San Bartolo lava flow, or alternatively a date of 1,500–2,000 BC, while recent paleomagnetic measurements (Speranza et al. 2008) obtained for this lava flow gave an age of 360 BC or 7 AD. Whatever the absolute age, the San Bartolo field is the youngest lava flow emplaced outside the Sciara del Fuoco.

A tectonic structure named Vallonazzo has been recognized by all previous authors (Rosi 1980; Keller et al. 1993), but no feeder dike, lava flows or spatter rampart of the associated eruptive activity have been distinguished, mapped and/or dated so far. In addition, the units that we have mapped on the N flank of the volcano (i.e. Labronzo, Serro Adorno, Spiaggia Lunga, Piscità and Vallonazzo, Fig. 1c) have been included by Keller et al. (1993) and Hornig-Kjarsgaard et al. (1993) among the undifferentiated Neostromboli lavas.

In this paper, we present a geological survey carried out between September 2005 and June 2007 on the NE sector of Stromboli, integrated with new  $^{40}\text{Ar}/^{39}\text{Ar}$  isotopic data (Wijbrans et al. 2010), petrographic and geochemical analyses. On this basis, we propose a new interpretation of the Holocene geology of the volcano, and re-evaluate the hazard for the opening of eruptive fissures on the NE flank of the island outside the barren Sciara del Fuoco depression.

## Stratigraphy

We have used lithostratigraphy as the basic criterion to identify volcanic units during our 1:10,000 scale field survey, as suggested by the International Stratigraphic Guide (ISG; Salvador 1994). The study area comprises effusive, explosive and epiclastic deposits, which on the whole represent the lithologic and morphologic history of the NE sector of the volcano. For this reason, we have used different ranks of lithostratigraphic units, such as formations, members, and “lava flows” (units comprising lavas emplaced in a single eruptive event). In accordance with the ISG, boundaries between lithostratigraphic units were based mainly on the recognition of the following

elements: 1) sharp lithological changes; 2) disconformity, pointed out by a hiatus marked by the presence of epiclastic deposits and/or paleosols; 3) erosion surface; 4) angular unconformity. Our “lava flows” are equivalent to the ISG rank “Flow—smallest distinctive layer in a volcanic sequence”, with “lava” added to indicate its dominance in all units including those containing other rock types. The geological field survey was integrated with the analyses of the 1987, 1:10,000 scale, colour aerial photos of the Compagnia Generale Riprese Aeree s.p.a., and using a collage from high-resolution orthophotos collected in 2001 and kindly provided by Maria Marsella (University of Roma “La Sapienza”).

We have recognised 11 lithostratigraphic units formed by lava flows, pyroclastic deposits and debris flow deposits; represented in Fig. 1c, they are described following their stratigraphic position from the base to the top. In particular, all the lithostratigraphic units are mapped at “Flow” rank (ISG) and represent the volcanic products erupted during a single eruptive event, corresponding to the “eruptive unit” of Fisher and Schmincke (1984), with the exception of the Osservatorio formation (see below).

The oldest products comprise the Osservatorio formation, that is formed by two members,  $\text{MO}_1$  and  $\text{MO}_2$ . The  $\text{MO}_1$  member is the lowest, and consists of massive and highly weathered lava flows that crop out mainly at Roisa locality along drainage gullies. These lava flows are locally disarticulated into large sub-rounded blocks due to erosion processes that have removed the scoriaceous portion. The  $\text{MO}_2$  member is made up of complex volcanoclastic deposits that crop out around the “Sentiero dei Fiorentini” path (Fig. 1c), covering the lava flows of the  $\text{MO}_1$  member. This volcanoclastic sequence shows a maximum observed thickness of 5 m, and comprises several layers up to 2.5 m thick, each representing single debris flow events. These deposits are massive, well consolidated, ungraded, both matrix- and clast-supported, with sandy matrix, angular lithic clasts up to 10–15 cm in size, and rare pumice clasts less than 1 cm long. The Sentiero dei Fiorentini unit is a pyroclastic fall deposit, 30 cm thick, made up of pumiceous lapilli ranging from white-yellow to dark grey in colour, that crops out discontinuously on top of the volcanoclastic sequence along the Sentiero dei Fiorentini path (Fig. 1c), from 90 m a.s.l. up to ~210 m a.s.l.

Further west from the Sentiero dei Fiorentini unit (Fig. 1c), the deeply eroded lava flows of the  $\text{MO}_1$  member of the Osservatorio formation are partially covered by the products of the Roisa unit. This unit crops out at Roisa locality (Fig. 1c), and consists of welded spatter with a total thickness of 10–20 m, forming an eruptive fissure ~160 m long, extending between 260 and 270 m elevation, and oriented  $\text{N}40^\circ\text{E}$ . The spatter rampart is composed of coarse spatter up to 50 cm, grey-red in colour, with evidences of



reomorphic flowage. A thick lava flow field (30–50 m) starts from the eruptive fissure, and is composed of several massive lava flow units that spread towards NE (Fig. 1c) up to the lowest elevation of ~90 m.

The San Vincenzo unit is mainly formed by a large scoria cone, ~500 m wide and 50–60 m high, cropping out between 20 and 70 m elevation below the Stromboli village and extending from the new cemetery to the San Vincenzo church (Fig. 1c). The scoria cone is made up of dark grey and reddish scoriaceous bombs up to 40 cm in size, and is breached towards NE. The cone is quite heavily eroded, with the crater area filled by recent alluvial deposits, and the outer slopes covered by a dark-brown epiclastic deposit. Although the original morphology of the scoria cone is partially eroded or buried by younger deposits, its shape is still clearly recognizable, evidencing a N55°E trend of the eruptive fissure (Fig. 1c). The lava flow related to the effusive phase of the San Vincenzo unit is preserved only in two small outcrops near Punta Lena, along the beach, in correspondence of the cone breaching (Fig. 1c).

The Labronzo unit is formed by a 40 m thick pile of stacked lava flows, forming the main portion of the costal cliff at Punta Frontone, on the northern margin of the study area (Fig. 1c). The direction of these lava flows lies between N50°E and N70°E, pointing to a source vent located outside the study area and further west. Each single flow unit is formed by massive grey-pink lava with grey-red scoria at the top and bottom (Fig. 2). On the whole, the lava flows are weathered and characterised by joint fractures. The sequence is fed by a dike, trending about E-W, cropping out at sea level (Figs. 1c, and 2).

The Spiaggia Lunga unit is formed by two lava flow units forming the base of the coastal cliff at the end of the Vallonazzo gully (Fig. 3). These lava flows also crop out along the wall of the Vallonazzo gully at ~250 m a.s.l. (Fig. 1c). The volcanic products of the Vallonazzo unit are related to a N40°E trending eruptive fissure, 700 m long,

extending from ~270 m a.s.l. to ~100 m a.s.l.. It fed a lava flow that reached the coast covering the Spiaggia Lunga unit (Figs. 1c and 3).

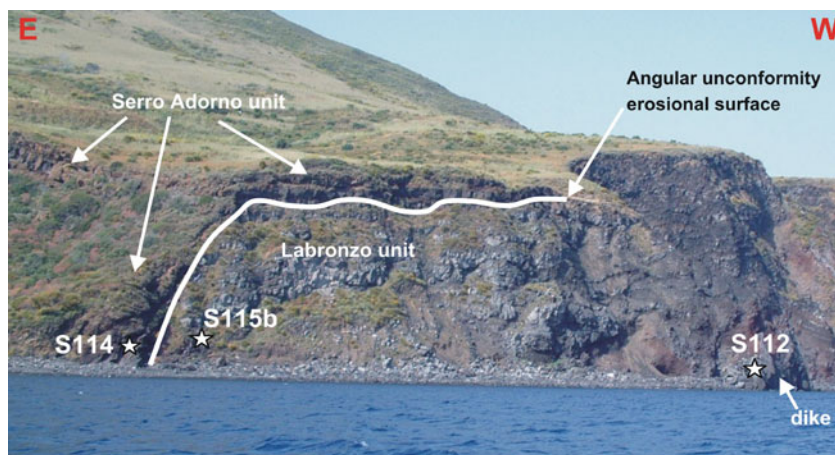
The spatter rampart deposit associated with the fissure crops out along the entire Vallonazzo valley, forming a low ridge at the two sides of the fissure. This deposit, 10–20 m thick, is composed of welded red spatter and scoria up to 50 cm in size. The feeder dike of this eruption is visible at 250 m a.s.l. in a small outcrop within the valley (Fig. 1c). The Vallonazzo eruptive fissure fed several superimposed flow units, with maximum observed thickness of ~7–8 m.

The volcanic products of the Nel Canestrà unit define an eruptive fissure oriented N50°E and ~700 m long, extending from ~500 m a.s.l. to ~150 m a.s.l. The fissure is composed of two segments with left-stepping en-echelon arrangement (Fig. 1c) consisting of spatter ramparts made of welded red and black spatter, up to 80 cm in size. The eruptive fissure forms two distinct ridges at ~450 m a.s.l. and ~200 m a.s.l., each reaching a maximum length of 400 m. This fissure generated both reomorphic lava flows close to the vent, 1–2 m thick, and lava flows further down slope, composed of several stacked grey-pink massive flow units that cover the Osservatorio formation and the San Vincenzo unit. The estimated total maximum thickness of the lava flow sequence is ~20–30 m (Fig. 1c).

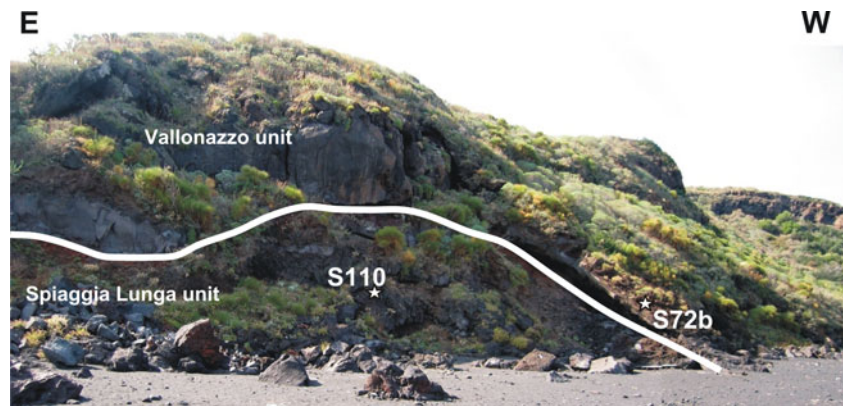
The Serro Adorno unit consists of a pyroclastic deposit forming an eruptive fissure trending N30°E, that fed a lava flow (Fig. 1c). The spatter ramparts comprising the fissure have an estimated maximum thickness of ~10 m and are composed of welded spatter up to 30 cm in size. The effusive portion is made up of at least two flow units, with a maximum thickness of 5–6 m, that covers the underlying weathered lava flows of the Labronzo unit with an angular unconformity (Fig. 2).

The Piscità unit is mainly composed of a pyroclastic deposit that forms a 300–400 m wide and ~30 m high scoria cone, made up of grey-red bombs and spatter up to

**Fig. 2** Punta Frontone site showing the contact between the units of Labronzo and Serro Adorno, and the location of the Labronzo feeder dike. The location of the analysed samples (S112, S114 and S115b) are shown with white stars. The angular unconformity and erosional surface separating the Labronzo and Serro Adorno units is also shown (white line). The cliff is about 100 m thick



**Fig. 3** Spiaggia Lunga beach sequence. Angular unconformity contact between a 3 m thick lava flow belonging to the Spiaggia Lunga unit (*below*), from which the sample S110 was collected, and the Vallonazzo unit (*above*), from which the sample S72b derives. The cliff is about 30 m thick



30 cm in size. This was produced by an eruptive fissure oriented N45°E, that forms an elongated hill immediately east of the San Bartolo church (Fig. 1c), and overlays the Roisa and Vallonazzo units. The Piscità eruptive fissure fed a massive lava flow, with a maximum observed thickness of 3–4 m, almost entirely buried by the San Bartolo lava flows.

The most recent volcanics of the study area are represented by the San Bartolo unit, fed by an eruptive fissure trending N45°E and extending from 270 m a.s.l. up to 600 m a.s.l., outside of the investigated area. The central portion of the lava flow field has buried a paleo-drainage gully carved between the Roisa and the Nel Cannestrà lava flows. Just at the sudden change in slope at ~40 m elevation along the coast, the San Bartolo lava flow forms a well exposed fan of rocky coastal cliff between Piscità and Ficogrande (Fig. 1c), where it is partially covered by recent alluvial deposit. The San Bartolo unit overlays the Roisa, Vallonazzo, Piscità and Nel Cannestrà units.

### Sampling and analytical techniques

The collection of rock samples was performed under a tight stratigraphic control. Only sample S108 is outside the study area (Fig. 1c), since it was collected from the top of the sequence and close to the Sciara rim to give a radiometric constraint to the last Sciara del Fuoco sector collapse (see paragraph 4 for details). The sample comes from a lava flow outcropping at Semaforo Labronzo locality at the top of the coastal cliff of Punta Labronzo at ~120 m elevation (Fig. 4), just below the Secche di Lazzaro pyroclastic deposits (Bertagnini and Landi 1996).

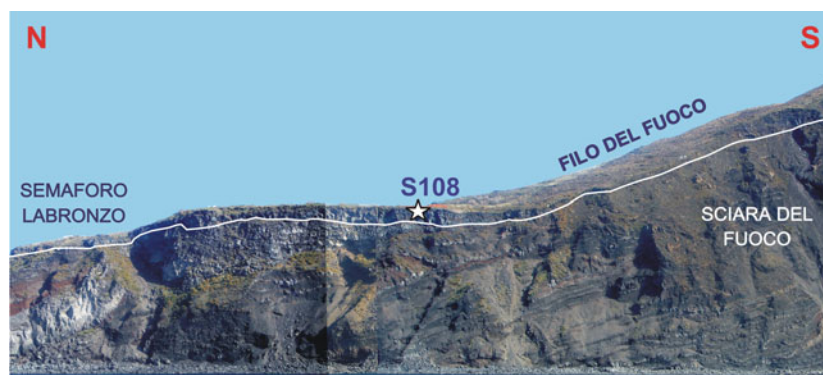
To characterise the stratigraphic sequence, we have collected a total of 50 samples, 24 of which were selected for petrographic study and chemical analyses. These mostly comprise lava flows, a few pyroclastic deposits, and one dike. Sample locations are shown in Fig. 1c and UTM coordinates using WGS 84 datum are reported in Table 1 (electronic annexe).

Whole-rock major (by ICP-AES) and trace elements (by ICP-MS) on whole rock powders have been performed at Centre National de la Recherche Scientifique, Vandoeuvre Les Nancy, Cedex, France. Analytical uncertainty is less than 1–2% for all major elements, except MnO and P<sub>2</sub>O<sub>5</sub> (less than 10%), and less than 5% for all trace elements except U (less than 8%). Whole rock major and trace element contents of all analysed samples are reported in Table 1 (electronic annexe).

Eleven samples have been analysed with the <sup>40</sup>Ar/<sup>39</sup>Ar method (Wijbrans et al. 2010). Of these, eight are lava flows (S65, S72b, S106, S108, S110, S114, S115b, and S117), two are spatter (S83 and S101), and one is a dike (S112). All of them have also been analysed for major and trace elements (Table 1; electronic annexe). Sample coordinates and a summary of results from Wijbrans et al. (2010) are reported in Table 2 (electronic annexe). Only sample S117, belonging to the San Bartolo unit, has not been reported, because its results are considered unreliable (Wijbrans et al. 2010).

### Results

Petrography and major and trace elements chemical analysis have been carried out on selected samples of the recognised stratigraphic succession, allowing us to characterise the petrographic and compositional features of the different lithostratigraphic units at their determined age. Petrography was determined on thin polished sections analysed with the LEO-1430 scanning electron microscope at Istituto Nazionale di Geofisica e Vulcanologia, sezione di Catania, which is equipped with an Oxford EDS microanalytical system. The lava flows of the Osservatorio formation (MO<sub>1</sub> member) are porphyritic, with a Porphyricity Index (P.I.=total phenocrysts abundance vol%) of 15 vol% and a mineral assemblage consisting of more abundant plagioclase than mafic phenocrysts (clinopyroxene, olivine and opaque oxide). The pumices of the



**Fig. 4** View from NW of the Punta Labronzo coastal cliff, formed by Neostromboli volcanics, as reported in the geological map of Keller et al. (1993). The white line indicates the base of the lava flow from which sample S108 was collected (white star), at about 100 m of

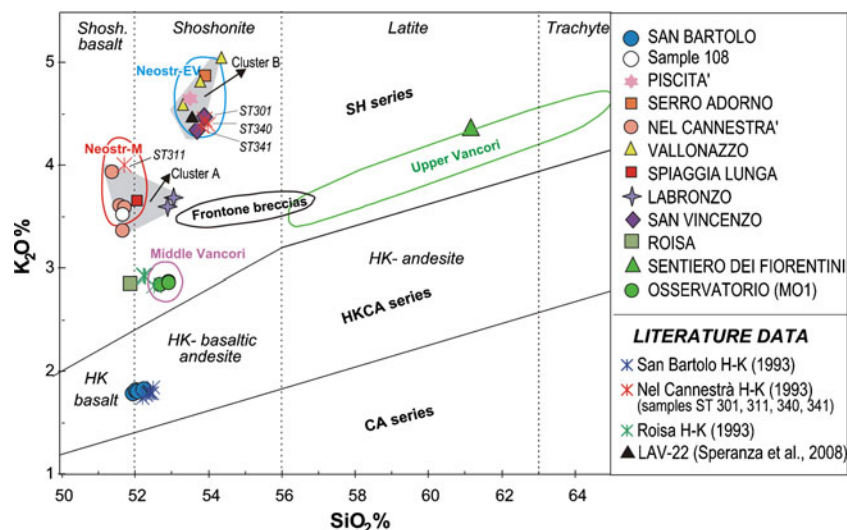
elevation. The feeder vent of this lava flow is not visible in this image but is located uphill. The lava flow is clearly cut by the cliff comprising the eastern scar of the Sciara del Fuoco (cfr. Fig. 1)

Sentiero Fiorentini unit are sub-afiric, with rare phenocrysts ( $>500\ \mu\text{m}$ ) of plagioclase and olivine, and abundant microcrysts of biotite and apatite. The products of Roisa unit have a P.I. variable between 15 and 20 vol%, with clinopyroxene prevailing over plagioclase, which appears strongly fractured. On the whole, the Osservatorio formation and the Sentiero Fiorentini and Roisa units plot in the field of the shoshonitic suite (SHO), and vary in composition from basalt to latite (Fig. 5).

The units of the stratigraphic sequence ranging from San Vincenzo to Piscit  (Fig. 1c) have a P.I. variable from 15 to 25 vol%. Plagioclase is more abundant than mafic phenocrysts (clinopyroxene, olivine and opaque oxide) in lavas of San Vincenzo, Vallonazzo and Serro Adorno units. By contrast, the products of Spiaggia Lunga, Labronzo and

Piscit  units have a lower plagioclase content than mafic minerals, whereas its proportion becomes comparable to mafic minerals in the Nel Cannestr  unit.

Crystals of plagioclase vary from mm to sub-mm in size. They are mostly euhedral, although sometimes appear strongly fractured and with corroded edges. Oscillatory zoning and sieve textures are common. Clinopyroxene is generally euhedral, with rare corroded edges and traces of alteration products in the joints. The crystals are frequently compositionally zoned and enclose opaque oxides and apatite. Olivine is generally euhedral, sub-mm in size and commonly embedding apatite crystals. Alteration often affects the joint surfaces or the whole crystal. Opaque oxide microlites ( $<50\ \mu\text{m}$ ) are usually observed in the groundmass, and in the Vallonazzo, Serro Adorno and



**Fig. 5**  $\text{K}_2\text{O}$  vs.  $\text{SiO}_2$  classification diagram (Peccerillo and Taylor 1976; Le Maitre 1989) for the studied volcanics. Clusters A and B (grey-coloured areas) comprise respectively the more mafic and more evolved rocks of the Neostromboli samples. Analyses from Hornig-Kjarsgaard et al. (1993) form the compositional fields of Neostromboli mafic rocks (Neostr-M, red circle), Neostromboli more evolved rocks

(Neostr-EV, blue circle), Upper Vancori (green circle), Frontone Breccias (black circle) and Middle Vancori (pink circle). In the legend, the literature data comprise distinct analyses of Hornig-Kjarsgaard et al. (1993) for Roisa, Nel Cannestr  and S. Bartolo (H-K). Sample LAV-22 is from Speranza et al. (2008). All data have been recalculated to 100% on a water-free basis



Piscità units they occur as mm-sized crystals. Finally, crystals of biotite from 350 to 50  $\mu\text{m}$  in size, commonly euhedral (Fig. 6a), occur in San Vincenzo, Vallonazzo, Nel Cannestrà, Serro Adorno and Piscità units.

The units of Vallonazzo, Nel Cannestrà and Piscità show biotite crystals (from 200 to 50  $\mu\text{m}$ ) in the inner wall of vesicles (Speranza et al. 2008) which probably formed under low pressure and high temperature conditions (Fig. 6b). These units also contain euhedral microcrystals ( $\sim 100 \mu\text{m}$ ) of apatite up to 1–2 vol% (Fig. 6c), mostly enclosed within clinopyroxene and olivine. Sometimes microlites of apatite ( $\sim 50 \mu\text{m}$ ) are observed in the groundmass (Fig. 6d).

The rocks of the stratigraphic succession from San Vincenzo to Piscità (Fig. 1) belong to a potassic series (KS), and despite their rather limited variability in  $\text{SiO}_2$  content (from 51.37 to 54.35%), they show a wide  $\text{K}_2\text{O}$  compositional range, spanning from 3.37 to 5.04. (Fig. 5; Table 1, electronic annexe). The KS volcanics form two clusters: one (cluster A, Fig. 5) comprises the more basic products of Labronzo unit, Spiaggia Lunga and Nel Cannestrà, which are essentially shoshonitic basalts and shoshonites (average  $\text{SiO}_2=51.86\pm0.47$ ,  $\text{TiO}_2=0.94\pm0.03$ ,  $\text{MgO}=5.24\pm0.40$ ,  $\text{CaO}=9.53\pm0.37$ ,  $\text{P}_2\text{O}_5=0.65\pm0.08$ ) with  $\text{K}_2\text{O}$  content less than 4%; the most evolved group (cluster B, Fig. 5) consists of the San Vincenzo, Vallonazzo, Serro Adorno and Piscità shoshonitic lavas (average  $\text{SiO}_2=53.78\pm0.34$ ,  $\text{TiO}_2=0.88\pm0.03$ ,  $\text{MgO}=3.56\pm0.33$ ,  $\text{CaO}=8.10\pm0.21$ ,  $\text{P}_2\text{O}_5=0.56\pm0.05$ ) with  $\text{K}_2\text{O}>4\%$ . Sample S108 shows a P.I. =15 vol%, with more abundant mafic minerals than plagioclase, and it plots in the more basic compositional field of KS volcanic (cluster A, Fig. 5). The most recent unit

of the volcanic succession is represented by San Bartolo lavas which are highly porphyritic, with average P.I.=40 vol %. They belong to the High-K Calc-alkaline (HKCA) series (Peccerillo and Taylor 1976), and are transitional between basalts and basaltic andesites (Fig. 5).

## Discussion

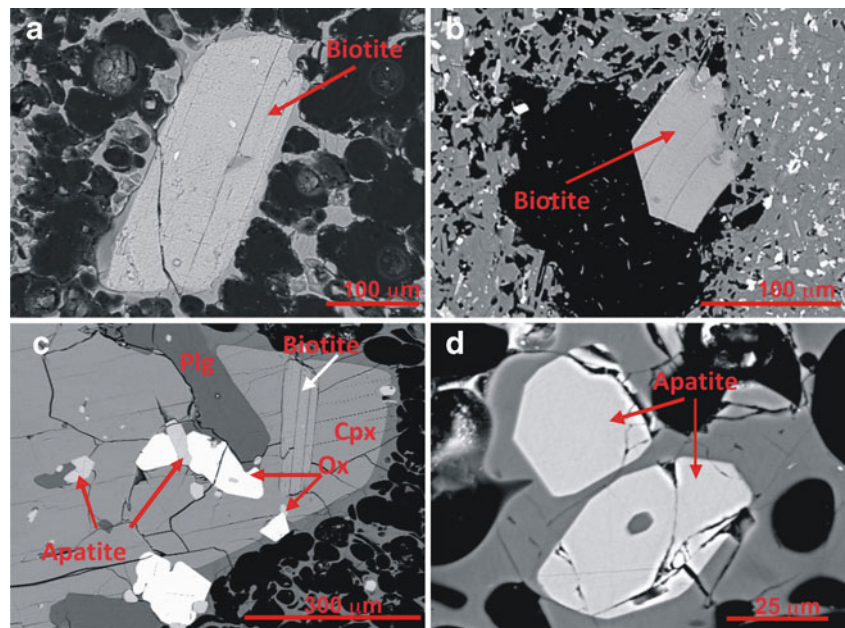
During our geological survey we have defined 11 lithostratigraphic units and 7 eruptive fissures on the NE flank of Stromboli (Fig. 1), temporally constrained by new  $^{40}\text{Ar}/^{39}\text{Ar}$  dating results (Wijbrans et al. 2010). The petrographic and geochemical features of the analysed samples proved important to characterise the different lithostratigraphic units and to define their correlation with the different volcanic edifices that were active since 15 ka (Fig. 7).

To compare our compositional data with those available in literature, we have selected the chemical analyses of Hornig-Kjarsgaard et al. (1993) and Speranza et al. (2008), because both were performed on stratigraphically well-constrained samples, thus easily comparable to our sampling.

### The new $^{40}\text{Ar}/^{39}\text{Ar}$ data

The relative age of the eruptive fissures recognised here has been obtained on the basis of lithostratigraphy, whereas geochronological ages have been measured on selected samples using new  $^{40}\text{Ar}/^{39}\text{Ar}$  dating obtained with novel techniques that are fully described in the companion paper (Wijbrans et al. 2010). These data are summarized in Table 2 (electronic annexe) and sample locations are

**Fig. 6** Backscattered images collected at the scanning electron microscope of: **a** biotite embedded in a vesiculated groundmass; **b** biotite located in the inner wall of a vesicle; **c** apatite enclosed in a clinopyroxene phenocryst; **d** apatite in a glassy groundmass





Period	$^{40}\text{Ar}/^{39}\text{Ar}$ age	Lithostratigraphic unit
Recent Stromboli	2 ka*	SB
	4 ka	PI
Neostromboli	7 ka	SA
		NC
		VA
	9 ka	SL
Vancori	12 ka	SV
		RO
		SF
	15 ka	OS

**Fig. 7** Schematic stratigraphic section of the NE flank of Stromboli Island with the relative position of the lithostratigraphic units described in this paper, and their corresponding  $^{40}\text{Ar}/^{39}\text{Ar}$  geochronology data from Wijbrans et al. (2010). The geological periods follow Hornig-Kjarsgaard et al. (1993) and Keller et al. (1993). The 2 ka\* age is from Arrighi et al. (2004) and Speranza et al. (2008). *OS* Osservatorio formation; *SF* Sentiero dei Fiorentini; *RO* Roisa; *SV* San Vincenzo; *LA* Labronzo; *SL* Spiaggia Lunga; *VA* Vallonazzo; *NC* Nel Cannestrà; *SA* Serro Adorno; *PI* Piscità; *SB* San Bartolo

reported in Fig. 1c. The significance of the new  $^{40}\text{Ar}/^{39}\text{Ar}$  data for the volcanic stratigraphy is discussed here.

Sample S101 comes from the oldest lava flow belonging to the Roisa unit and crops out on the lower NE flank of the volcano (Fig. 1c). The resulting weighted plateau age is  $15.2 \pm 2.8$  ka (error in  $1\sigma$ ), and is in good agreement with stratigraphy. However, the mean squared weighted deviation (MSWD) is 2.2, very close but still below the limit of 2.5 fixed by Dunai and Wijbrans (2000) to consider the result reliable.

Sample S65 was collected from the San Vincenzo lava flow at Punta Lena locality along the coast (Fig. 1c), where a massive lava flow crops out at 1 m a.s.l. The weighted plateau age results  $12.5 \pm 2.6$  ka, which is again in agreement with its stratigraphic position. Samples S112 and S115b come from a dike and a lava flow which intruded the Labronzo lava flow unit respectively (Fig. 1c), and their weighted plateau ages are  $8.2 \pm 1.8$  ka and  $8.3 \pm 1.6$  ka. Two samples were collected from the lava flow sequence cropping out at the Spiaggia Lunga beach. The first one, S110, was collected from the lower lava flow belonging to the Spiaggia Lunga unit (Fig. 3), and it gave an age of  $7.7 \pm 1.4$  ka. The second sample, S72b, was collected from a lava flow belonging to the Vallonazzo unit which covers the Spiaggia Lunga unit lava flow (Fig. 3). The weighted plateau age of sample S72b is  $8.7 \pm 2.0$  ka. Considering the measurement error, the ages of the two lava flows overlap, and for this reason they can be considered as coeval.

The S83 spatter was collected very close to the eruptive fissure from the Nel Cannestrà unit, and its age results  $7.9 \pm 1.2$  ka. Sample S114 was taken from a lava flow belonging to the Serro Adorno unit, and cropping out along the coast a few meters ESE of Punta Frontone locality (Fig. 2). The weighted plateau age results  $6.9 \pm 1.1$  ka. Sample S106 was collected from a lava flow belonging to the Piscità unit cropping NW of the San Bartolo church. The weighted plateau age is  $6.8 \pm 1.4$  ka.

Sample S108 was collected outside the study area, from a lava flow located at Semaforo Labronzo locality at the top of the coastal cliff of Punta Labronzo at ~120 m elevation (Fig. 2), just below the Secche di Lazzaro pyroclastic deposits (Bertagnini and Landi 1996). In particular, this lava flow is at the top of the Sciarra del Fuoco rim at Semaforo Labronzo locality (Fig. 6). The weighted plateau age of sample S108 was calculated as the average of two duplicate runs and results in  $4.0 \pm 0.9$  ka.

Finally, sample S117 is the youngest lava flow of the studied area, collected along the coast at the eastern margin of the Spiaggia Lunga locality, and belonging to the San Bartolo unit. On this sample we have obtained an unexpected old age ( $13.1 \pm 4.6$  ka) that is inconsistent with the stratigraphic position. Therefore, we consider the  $^{40}\text{Ar}/^{39}\text{Ar}$  age of this particular sample of poor quality because of its extremely low enrichment in radiogenic  $^{40}\text{Ar}$  resulting from its historical age (Arrighi et al. 2004; Speranza et al. 2008).

### Volcanic stratigraphy

**Vancori period** The oldest lithostratigraphic unit, here named Osservatorio formation, belongs to the Upper Vancori unit in the geological map of Keller et al. (1993) that, at Gramigna locality, was dated with K/Ar at  $13.0 \pm 1.9$  ka by Gillot and Keller (1993). The Osservatorio shoshonitic lavas ( $\text{MO}_1$  member) match very well (Figs. 4, and 8) the compositional range of volcanics belonging to the Middle Vancori recognised by Hornig-Kjarsgaard et al. (1993).

Thus, on the basis of our data, the Middle Vancori outcrops can be extended further north-eastward than previously known (Keller et al. 1993). The latite of the Sentiero dei Fiorentini pumice unit clearly overlaps the compositional field (Fig. 4) of the Upper Vancori volcanic rocks of Hornig-Kjarsgaard et al. (1993), and thus represents the end of the Vancori phase of activity.

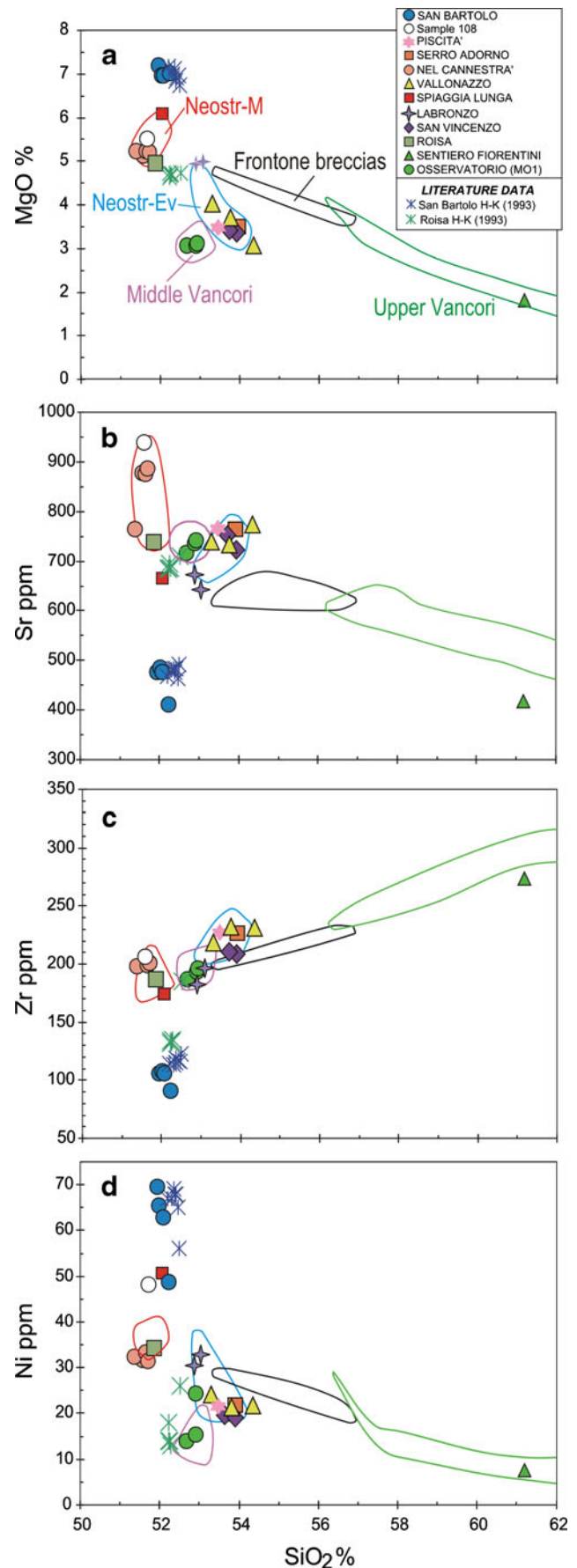
The oldest eruptive fissure recognised in this study belongs to the Roisa unit ( $15.2 \pm 2.8$  ka, S101), that covers the lava flows of the Osservatorio formation with a clear stratigraphic contact at ~350 m a.s.l. The Roisa unit was already mapped by Keller et al. (1993), who also described its feeder dikes, welded spatter and lava flow, but we have

**Fig. 8** SiO<sub>2</sub> vs. **a** MgO, **b** Sr, **c** Zr, **d** Ni for the volcanics studied in this paper. Symbols and literature data as in Fig. 5. The Nel Cannestrà analyses from Hornig-Kjarsgaard et al. (1993) plotted in Fig. 5 are here included in the Neostr-M and Neostr-EV compositional fields. All data have been recalculated to 100% on a water-free basis

also mapped the eruptive fissure, distinguishing the lava flow from the proximal pyroclastic deposit. The compositional characteristics of the Roisa lavas do not allow assigning these products unequivocally to a specific unit of the stratigraphic succession. In fact, the Roisa lavas are significantly different from the Upper Vancori and Frontone Breccia volcanics (Hornig-Kjarsgaard et al. 1993). Furthermore, the K<sub>2</sub>O content of the Roisa lavas make them very close to the Middle Vancori products (Fig. 5), whereas the content of MgO and selected trace elements evidence their affiliation with the more mafic Neostromboli rocks (Fig. 8). On the basis of compositional characteristics, we therefore prefer to consider the Roisa unit as transitional between the Vancori and Neostromboli periods, although more detailed analyses on a larger data set are needed to clarify the role of the Roisa unit within the stratigraphic succession.

**Early Neostromboli period** The San Vincenzo unit is mainly formed by the products of an eruptive fissure, identified here for the first time, and consisting of a large scoria cone that crops out below the village of Stromboli. The lava flow erupted from this fissure is exposed only in two small outcrops at Punta Lena, previously attributed to the Nel Cannestrà lava (Keller et al. 1993). We have obtained an <sup>40</sup>Ar/<sup>39</sup>Ar age of 12.5±2.6 ka for the San Vincenzo lava flow, evidencing that it was emplaced when the paleo-shoreline was ~70–75 m below the present sea level (Lambeck et al. 2004). This is also testified by direct observation on the underwater portion of this lava flow field that shows a subaerial surface morphology up to ~30 m depth below sea level.

The San Vincenzo lavas show a shoshonitic composition which plots in the field of the Neostromboli more evolved rocks available in literature (Neostr-EV field, in Figs. 5 and 8), and are much more differentiated than the Roisa shoshonitic basalts which were erupted ~3,000 years earlier. The comparison with literature data reveals a good match between our San Vincenzo lavas and samples ST301, ST340 and ST341 (Fig. 5) attributed by Hornig-Kjarsgaard et al. (1993) and Keller et al. (1993) to the Nel Cannestrà lava flow. Overlapping the position of their ST301, ST340 and ST341 samples to our geological map, we can see that these belong to what we have mapped as the San Vincenzo unit, as also confirmed by the compositional data (Fig. 5). Also the LAV-22 sample assigned to the Nel Cannestrà unit by Speranza et al. (2008) on the basis of the Hornig-Kjarsgaard et al. (1993) attribution, matches the composition of the San Vincenzo lavas very well (Fig. 5).



**Main Neostromboli period** Since 9 ka, several flank eruptions occurred on the lower NE flank of the island. In particular, six eruptions took place in a period of only 2,000 years, between ~9 and 7 ka, evidencing a phase of frequent lateral intrusions and intense eruptive activity. The products of these eruptions in the geological map of Keller et al. (1993) were indistinctly grouped in the Neostromboli lavas, with the exception of the Nel Canestrà lava.

The lava flows of Labronzo unit forming the coastal cliff at Punta Frontone are fed by a dike trending E-W and cropping out at sea level, that gave an age of  $8.3 \pm 1.6$  ka and  $8.2 \pm 1.8$  ka respectively. Given the presence of a large subvolcanic body located at Punta Labronzo, immediately west of Punta Frontone, dated with K/Ar at  $5.6 \pm 3.3$  ka by Gillot and Keller (1993), it appears that shallow intrusions occurred close to the north coastline between ~8.3 and 5.6 ka.

The lava flow of the Spiaggia Lunga unit ( $7.7 \pm 1.4$  ka) is mostly covered by the Vallonazzo unit products ( $8.7 \pm 2.0$  ka) and its eruptive fissure is not exposed in the study area. Although these two geochronological dates seem inverted when compared to their stratigraphic position (Fig. 3), the uncertainty of the calculated age makes the two units coeval.

The Nel Canestrà unit lava, that Wijbrans et al. (2010) have dated at  $7.9 \pm 1.2$  ka, overlaps the much older scoria cone of the San Vincenzo unit. The frontal portion of this lava field is covered by recent alluvial deposit.

The Serro Adorno and Piscità units are almost coeval, and have been dated by Wijbrans et al. (2010) at  $6.9 \pm 1.1$  ka and  $6.8 \pm 1.4$  ka, respectively. The Serro Adorno lava flow unit covers with an angular unconformity the lava flows of the Labronzo unit, that at the time of this eruption formed a paleo-coastal cliff. The Piscità lava flow unit is almost entirely buried by the San Bartolo unit.

The products erupted during the main Neostromboli period belong to the compositional field of Neostromboli volcano (Hornig-Kjarsgaard et al. 1993) and cluster in two different groups, as already observed by Hornig-Kjarsgaard et al. (1993) and confirmed by Speranza et al. (2008). The less evolved rocks of Labronzo, Spiaggia Lunga and Nel Canestrà (cluster A in Fig. 5) mostly overlap the compositional field of the more mafic Neostromboli sequence available in literature (Neostr-M field, in Figs. 5 and 8), whilst San Vincenzo, Vallonazzo, Serro Adorno and Piscità units (cluster B in Fig. 5) correspond to the most evolved term of the literature succession (Neostr-Ev field, in Figs. 5 and 8). From our data, the clustering of rocks in these two distinct groups appears independent from the geographic location of samples and from their stratigraphic position.

**Recent Stromboli period** After the Serro Adorno and Piscità flank eruptions, at least 5,000 years elapsed before the next and most recent flank eruption in the NE portion of the

island, emplacing the San Bartolo unit. This lava flow was dated  $100 \pm 100$  AD by Arrighi et al. (2004) with archeomagnetic technique, and 360 BC or 7 AD by Speranza et al. (2008) that used a paleomagnetic technique. Both major (Figs. 5 and 8a) and trace elements (Fig. 8b, c, d) composition of the San Bartolo lavas overlap their literature counterparts (see Hornig-Kjarsgaard et al. 1993; Speranza et al. 2008).

#### Age correlation

The geochronological results by Wijbrans et al. (2010) partially confirm the paleomagnetic data of Speranza et al. (2008), as shown in Table 3 (electronic annexe).

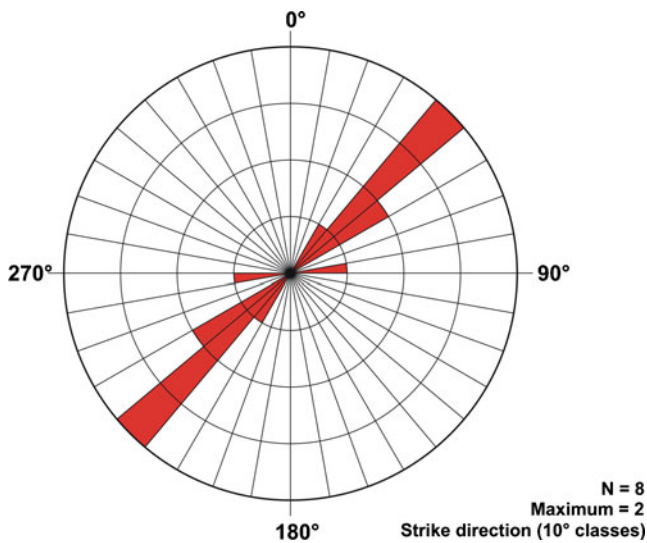
However, for the case of sample S65 (San Vincenzo unit,  $12.5 \pm 2.6$  ka) we found a large discrepancy when compared to the value of 6.2 ka obtained by Speranza et al. (2008). Our stratigraphic data clearly indicate that the San Vincenzo scoria cone is covered by the Nel Canestrà lava flows ( $7.9 \pm 1.2$  ka, S83), and the radiometrical results by Wijbrans et al. (2010) confirmed this evidence. In addition, the new age for the San Vincenzo eruption is also in agreement with the subaerial morphology of the San Vincenzo lava flow, at present located below sea level. If we consider an age of 6.2 ka for this lava flow, at that time the paleo-shoreline was located only at ~8 m below the present sea level (Lambeck et al. 2004), and this cannot explain the subaerial morphology of the San Vincenzo lavas observed up to at least 30 m below sea level. Finally, our geochronological result for the S108 lava flow, forming the top of the Sciara del Fuoco rim ( $4.0 \pm 0.9$  ka) at Semaforo Labronzo locality and discussed in detail in the companion paper by Wijbrans et al. (2010), allowed us to define the upper boundary of Neostromboli, and to constrain the age of the most recent Sciara del Fuoco flank collapse.

#### Structural significance

From a structural point of view the geometry of the eruptive fissures on the NE flank of Stromboli were measured because their orientation reflects the geometry of the shallow magma feeding system, which is related to the volcano structure and dynamics (Nakamura 1977; Fink and Pollard 1983; Tibaldi 1995; Norini et al. 2008). The recognized eruptive fissures in the Vancori-Neostromboli-Recent Stromboli periods show a small variability of the strike directions. The mean azimuth of these fissures is  $N45^\circ E$  (Fig. 9).

The data are consistent with eruption feeding intrusions oriented  $N30^\circ E$ – $N55^\circ E$ , radiating from the magma feeding system of the volcano. According to Pasquaré et al. (1993) and Tibaldi (1996, 2003), the intrusions developed prefer-





**Fig. 9** Rose diagram showing azimuth of the eight eruptive fissures recognised on the NE flank of Stromboli. The azimuths are plotted based on the number of fissures

entially along a NE-trending rectilinear axial zone, consistent with the transmission of regional tectonic stress (i.e. a NW–SE sigma 3) to the volcanic edifice, and thus to the magma feeding paths.

## Conclusions

Our new geological survey, supported by  $^{40}\text{Ar}/^{39}\text{Ar}$  isotopic age determinations and by petrographic and geochemical analyses of the stratigraphic units identified, allowed us to better define the eruptive history since 15 ka for this sector of the volcano, where the Neostromboli volcanics emplaced on the Vancori products (Fig. 7).

The oldest eruptive fissure recognised in this sector of the volcano is Roisa, which has an age of  $15.2 \pm 2.8$  ka. It thus belongs to the Vancori period, even if the composition of its lavas seems to be transitional towards the products erupted during the Neostromboli period. Our geological survey indicates the San Vincenzo eruptive fissure as the earliest flank eruptive event of the Neostromboli period, with an age of  $12.5 \pm 2.6$  ka.

After a 4,000 year of eruptive pause, an intense phase of high frequency flank eruptions occurred between  $\sim 9$  and 7 ka, with the emplacement of the Labronzo, Spiaggia Lunga, Vallonazzo, Nel Cannestrà, Serro Adorno and Piscità volcanics. This phase of intense effusions is related to the NE trending magma intrusion zone of the volcano (Fig. 9). We suggest that this high rate of lateral intrusion occurring in a short time span might have promoted the north-westward dilation of the volcano edifice and thus the flank collapse of the Sciara del Fuoco slope (Moriya 1980;

Siebert 1984; Tibaldi 1996). Alternatively, this high rate of intrusion along the NE trend might be the result of the reorientation of the local stress field due to the collapse of the Sciara del Fuoco (McGuire et al. 1990; Acocella et al. 2009). The new date of  $4.0 \pm 0.9$  ka (Wijbrans et al. 2010), obtained on the lava flow (S108) at the top of the sequence forming the Sciara del Fuoco rim along the Filo del Fuoco-Semaforo Labronzo locality, constrains the last Sciara del Fuoco collapse (Fig. 4). Indeed, this lava flow is covered only by the Secche di Lazzaro pyroclastic deposit that emplaced during the last Sciara del Fuoco collapse (Bertagnini and Landi 1996). In particular, according to the multiple sector collapses phenomena reconstructed for Stromboli by Tibaldi (2001), we can assert that the most recent flank collapse is younger than 4 ka. In addition, the compositional affinity between the S108 lava flow and the Neostromboli volcanics, suggests that this lava flow represents the top of the Neostromboli sequence cropping out on this side of the volcano.

The overall petrographic and compositional variability of the Neostromboli products allowed obtaining basic information about the characteristics of the volcano plumbing system from  $\sim 15$  to 4 ka. We believe that in this period the Neostromboli volcano was fed by a zoned magma chamber which, depending on the geometry and vertical extension of the eruptive fissures, drained magmas at different degree of evolution. Alternatively, we cannot exclude that inputs of new, more primitive magmas from depth repeatedly intruded the Neostromboli reservoir, where they differentiated by mixing and crystallisation processes, causing the eruption of products with various composition. The occurrence of magma chambers open to the recharge of new magmas from depth has already been proposed to explain the transition between Upper Vancori and Neostromboli and the chemical variation occurring within both Lower Vancori and Middle Vancori sequence (Franclanci et al. 1989; Cortés et al. 2005). The 2,000 years of time elapsed between the end of the Neostromboli activity and the Recent Stromboli eruption of the San Bartolo lava flows was enough to allow substantial degassing and fractionation before eruption (Laiolo and Cigolini 2006). This is in agreement with the lower sequence of pyroclastic falls described by Rosi et al. (2000) for this period of time, although we cannot exclude that effusive activity might have occurred also within the Sciara del Fuoco. From our reconstruction of the eruptive activity on the NE flank of the volcano, the period between 9 and 7 ka proved highly productive in terms of lateral lava effusions. Lateral displacement triggered by the many feeder dike intrusions might have favoured flank collapses of the Sciara del Fuoco during this period, or, alternatively, the collapses of the Sciara del Fuoco might have conditioned the direction of emplacement of these feeder dikes.

**Acknowledgements** The mapping of Stromboli was supported by a grant to S. Calvari (Project V2/01, 2005–2007, funded by the Istituto Nazionale di Geofisica e Vulcanologia and by the Italian Civil Protection). This work was partly supported by INGV through a research grant financed by MIUR-FIRB to G. Norini. We wish to thank the former Director of INGV-Sezione di Catania, A. Bonaccorso, for making additional funds available for field trip and datings; M. Marsella for the wonderful 2001 orthophotos that added so much information to our work; J. Keller for the many and precious discussions and suggestions on the geology of Stromboli; and the BV Associate Editor B. van Wyk de Vries and Executive Editor J.D.L. White for their useful suggestions that helped improve the clarity of the paper. We are also indebted to M. Di Vito, G. Groppelli, L. Lodato, M. Neri and G. Orsi for fruitful discussions during the geological survey, to G. Lanzafame for his many suggestions and discussions about the structural interpretation, and to L. Messina for preparing powder for rocks analyses. Stephen Conway improved the English style.

## References

- Acocella V, Neri M, Sulpizio R (2009) Dike propagation within active central volcanic edifices: constraints from Somma-Vesuvius, Etna and analogue models. *Bull Volc* 71:219–223
- Arrighi S, Rosi M, Tanguy JC, Courtillot V (2004) Recent eruptive history of Stromboli (Aeolian Islands, Italy) determined from high-accuracy archeomagnetic dating. *Geoph Res Lett* 31: (L19603), doi:10.1029/2004GL020627
- Barberi F, Rosi M, Sodi A (1993) Volcanic hazard assessment at Stromboli based on review of historical data. *Acta Vulc* 3:173–187
- Bertagnini A, Landi P (1996) The Secche di Lazzaro pyroclastic of Stromboli volcano: a phreatomagmatic eruption related to the Sciara del Fuoco sector collapse. *Bull Volc* 58:239–245
- Bertagnini A, Coltelli M, Landi P, Pompilio M, Rosi M (1999) Violent explosions yield new insights into dynamics of Stromboli volcano. *Eos Am Geoph Union Trans* 80:633–636
- Bonaccorso A, Calvari S, Garfi G, Lodato L, Patané D (2003) Dynamics of the December 2002 flank failure and tsunami at Stromboli volcano inferred by volcanological and geophysical observations. *Geoph Res Lett* 30:1941–1944
- Branca S, Del Carlo P (2005) Types of eruptions of Etna volcano AD 1670–2003: implications for short-term eruptive behaviour. *Bull Volc* 67:732–742
- Calvari S, Spampinato L, Lodato L (2006) The 5 April 2003 vulcanian paroxysmal explosion at Stromboli volcano (Italy) from field observations and thermal data. *Jour Volc Geoth Res* 149:160–175
- Cortés JA, Wilson M, Condliffe E, Francalanci L, Chertkoff DG (2005) The evolution of the magmatic system of Stromboli volcano during the Vancori period (26–13.8 ky). *Jour Volc Geoth Res* 147:1–38
- Dunai TJ, Wijbrans JR (2000) Long-term cosmogenic  $^3\text{He}$  production rates (152 ka–1.35 Ma) from  $^{40}\text{Ar}/^{39}\text{Ar}$  dated basalt flows at 29° N latitude. *Earth Plan Sci Letter* 176:147–156
- Fink JH, Pollard DD (1983) Structural evidence for dikes beneath silicic domes, Medicine Lake Highland Volcano, California. *Geology* 11:458–461
- Fisher RV, Schmincke HU (1984) *Pyroclastic rocks*. Springer-Verlag, 1984, pp. 472
- Francalanci L, Manetti P, Peccerillo A (1989) Volcanological and magmatological evolution of Stromboli volcano (Aeolian islands): the roles of fractional crystallisation, magma mixing, crustal contamination and source heterogeneity. *Bull Volc* 51:355–378
- Gillot PY, Keller J (1993) Radiochronological dating of Stromboli. *Acta Vulc* 3:69–77
- Hornig-Kjarsgaard I, Keller J, Koberski U, Stadlbauer E, Francalanci L, Lenhart R (1993) Geology, stratigraphy and volcanological evolution of the island of Stromboli, Aeolian arc, Italy. *Acta Vulc* 3:21–68
- Keller J, Hornig-Kjarsgaard I, Koberski U, Stadlbauer E, Lenhart R (1993) Geological map of the island of Stromboli - scale 1:10.000. *Acta Vulc* 3:appendix
- Laiolo M, Cigolini C (2006) Mafic and ultramafic xenoliths in San Bartolo lava field: New insights on the ascent and storage of Stromboli magmas. *Bull Volc* 68:653–670. doi:10.1007/s00445-005-0040-7
- Lambeck K, Antonioli F, Purcell A, Silenzi S (2004) Sea-level change along the Italian coast for the past 10, 000 yr. *Quat Sci Reviews* 23:1567–1598
- Le Maitre RW (Ed.) (1989) *A classification of igneous rocks and glossary of terms*, Blackwell Scientific Publications, pp. 193
- McGuire WJ, Pullen AD, Saunders SJ (1990) Recent dyke-induced large-scale block movement at Mount Etna and potential slope failure. *Nature* 343:357–359
- Moriya I (1980) Bandaian eruption and landforms associated with it. Collection of articles in memory of retirement of Prof. K. Hishimura: Tokyo, Tohoku University, 66:214–219
- Nakamura K (1977) Volcanoes as possible indicators of tectonic stress. *Jour Volc Geoth Res* 2:1–16
- Norini G, Capra L, Groppelli G, Lagmay AMF (2008) Quaternary sector collapses of Nevado de Toluca volcano (Mexico) as consequence of regional tectonics and volcanic evolution. *Geosphere* 4:854–871
- Pasquaré G, Francalanci L, Garduno VH, Tibaldi A (1993) Structure and geological evolution of the Stromboli volcano, Aeolian islands, Italy. *Acta Vulcanologica* 3:79–89
- Peccerillo A, Taylor SR (1976) Geochemistry of Eocene calc-alkaline volcanic rocks from Kastamonu area, Northern Turkey. *Contr Min Petr* 58:63–81
- Rittmann A (1931) Der ausbruch des Stromboli am 11 September 1930. *Zeitschrift für vulkanologie* 14:47–77
- Rosi M (1980) The island of Stromboli. *Rend Soc It Min Petr* 36:345–368
- Rosi M, Bertagnini A, Landi P (2000) Onset of the persistent activity at Stromboli Volcano (Italy). *Bull Volc* 62:294–300
- Salvador A (1994) *International Stratigraphic Guide*. Geological Society of America, Salvador A. editor, Boulder, pp. 214, online site: <http://www.stratigraphy.org/column.php?id=Stratigraphic%20Guide>
- Siebert L (1984) Large volcanic debris avalanches: characteristics of source areas, deposits, and associated eruptions. *Jour Volc Geoth Res* 22:163–197. doi:10.1016/0377-0273(84)90002-7
- Speranza F, Pompilio M, D'Ajello Caracciolo F, Sagnotti L (2008) Holocene eruptive history of the Stromboli volcano: constraints from paleomagnetic dating. *Jour Geoph Res* 113(B09101):1–23. doi:10.1029/2007JB005139
- Tibaldi A (1995) Morphology of pyroclastic cones and tectonics. *Jour Geoph Res* 100:24521–24535
- Tibaldi A (1996) Mutual influence of diking and collapses at Stromboli, Aeolian Arc, Italy: in volcano instability in the earth and other planets. *Spec Publ Geol Soc London* 110:55–63
- Tibaldi A (2001) Multiple sector collapses at Stromboli volcano, Italy: how they work. *Bull Volcanol* 63:112–125. doi:10.1007/s004450100129
- Tibaldi A (2003) Influence of cone morphology on dykes, Stromboli, Italy. *Jour Volc Geoth Res* 126:79–95
- Wijbrans JR, Schneider B, Calvari S, Branca S, De Beni E, Norini G, Corsaro RA, Miraglia L (2010)  $^{40}\text{Ar}/^{39}\text{Ar}$  geochronology of Holocene basalts; examples from Stromboli, Italy. Manuscript in press in the *Journal of Quaternary Geochronology*